PDHonline Course C732 (4 PDH)

Roadway Vertical Alignments

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Gregory J. Taylor, P.E.

INTRODUCTION

Roadway vertical alignments are a combination of various parabolic curves and connecting tangent grades. It is one of the fundamental three-dimensional road features directly related to safety, operations, drainage, and construction requirements. Together with the horizontal alignment (tangents and curves) and roadway cross-sections (lanes, shoulders, curbs, medians, roadside slopes, ditches, sidewalks), the vertical alignment (grades and vertical curves) help provide a three-dimensional roadway layout.

This course focuses on the geometric design of **vertical alignments** for modern roads and highways. Its contents are intended to serve as guidance and not as an absolute standard or rule.

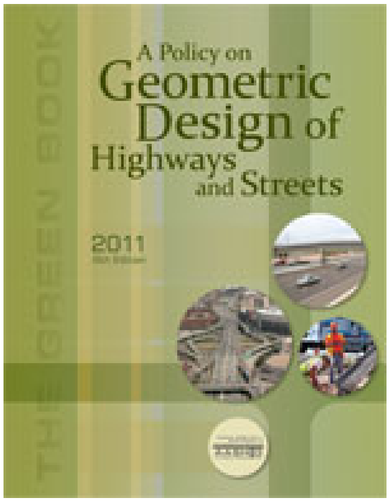
Upon course completion, you should be familiar with the general design of vertical roadway alignments. The course objective is to give engineers and designers an in-depth look at the principles to be considered when designing vertical alignments.

Subjects covered include:

- Sight Distance
  - Stopping
  - Decision
  - Passing
  - Intersection
- Vertical Alignment
  - Grades
  - Climbing lanes
  - Passing opportunities
  - Emergency escape ramps
- Vertical Curves
  - Sag
  - Crest
- Coordination of Horizontal & Vertical Curves

A Policy on Geometric Design of Highways and Streets (also known as the "Green Book") published by the American Association of State Highway and Transportation

Officials (AASHTO) is considered to be the primary guidance for U.S. roadway design. For this course, Chapter 3 (Section 3.4 Vertical Alignment) will be used exclusively for fundamental roadway geometric design principles.



BACKGROUND

Roadway geometric design consists of the following fundamental three-dimensional features:

Vertical alignment - grades and vertical curves

Horizontal alignment - tangents and curves

Cross section - lanes and shoulders, curbs, medians, roadside slopes and ditches, sidewalks

Combined, these elements contribute to the roadway's operational quality and safety by providing a smooth-flowing, crash-free facility.

Engineers must understand how all of the roadway elements contribute to overall safety and operation. Applying design standards and criteria to 'solve' a problem is not enough.

The fundamental objective of good geometric design will remain as it has always been **– to produce a roadway that is safe, efficient, reasonably economic and sensitive to conflicting concerns.**

SIGHT DISTANCE

Sight distance is the length or distance of roadway visible to the driver. This is a major design control for vertical alignments and is essential for the safe and efficient operation of vehicles. This distance is dependent on the driver's eye height, the specified object height, and the height/position of sight obstructions. The three-dimensional features of the roadway should provide a minimum sight line for safe operations.

Sight Distance Criteria

Height of Driver's Eye:	3.50 feet above road surface (passenger vehicles)
	7.60 feet above road surface (trucks)
Height of Object:	2.00 feet above road surface (stopping & decision)
	3.50 feet above road surface (passing & intersection)

Due to differences in driver needs, various types of sight distance apply to geometric design **stopping,** **decision,** **passing,** and **intersection**.

STOPPING SIGHT DISTANCE (SSD)

Stopping sight distance is considered to be the most basic form of sight distance. This distance is the length of roadway needed for a vehicle traveling at design speed to stop before reaching a stationary object in the road. Ideally, all of the roadway should provide stopping sight distance consistent with its design speed. However, this distance can be affected by both horizontal and vertical geometric features.

Stopping sight distance is composed of two distances:

(1) Brake Reaction Time starts upon driver recognition of a roadway obstacle until application of the vehicle's brakes. Typically, the driver not only needs to see the object but also recognize it as a potential hazard. The time required to make this determination can widely vary based on the object's distance, visibility, roadway conditions, vehicle speed, type of obstacle, etc.

Perception → Braking

From various studies, it was shown that the required brake reaction time needed to be long enough to encompass the majority of driver reaction times under most roadway conditions. A brake reaction time of 2.5 seconds met the capabilities of most drivers – including older drivers.

The recommended brake reaction time of **2.5 seconds** exceeds the 90th percentile of driver reaction time and is considered adequate for typical roadway conditions – but not for most complex driving conditions that may be encountered.

(2) Braking Distance – Roadway distance traveled by a vehicle during braking (from the instant of brake application)

Braking → Stopping

Using the following equation, the approximate braking distance (d_B) may be calculated for a vehicle traveling at design speed on a level roadway. The recommended deceleration rate (a) of **11.2 ft/s²** has shown to be suitable since 90% of all drivers decelerate at greater values. This deceleration rate is fairly comfortable and allows drivers to maintain steering control.

$$d_B = 1.075 \frac{V^2}{a}$$

d_B = braking distance (feet)

V = design speed (mph)

a = deceleration rate (ft/sec^2)

For roadways on a grade, the braking distance can be determined by:

$$d_B = \frac{V^2}{30\left[\left(\frac{a}{32.2}\right) +/- G\right]}$$

d_B = braking distance on grade (feet)

V = design speed (mph)

a = deceleration rate (ft/sec^2)

G = grade (ft/ft)

Stopping distances for downgrades are longer than those needed for level roads while those on upgrades are shorter.

The Stopping Sight Distance formula is a function of initial speed, braking friction, perception/reaction time, and roadway grade that contains assumptions about the driver's eye height (3.5 feet) and the size of object in the road (2 feet).

$$SSD = 1.47Vt + 1.075\frac{V^2}{a}$$

SSD = stopping sight distance (feet)

V = design speed (mph)

a = deceleration rate (ft/sec^2)

Stopping Sight Distance - Level Roadways

Design Speed (mph)	Brake Reaction Distance (ft)	Braking Distance (ft)	Stopping Sight Distance	
			Calculated (ft)	Design (ft)
20	73.5	38.4	111.9	115
30	110.3	86.4	196.7	200
40	147.0	153.6	300.6	305
50	183.8	240.0	423.8	425
60	220.5	345.5	566.0	570
70	257.3	470.3	727.6	730
80	294.0	614.3	908.3	910

Source: AASHTO "Green Book" Table 3-1

Limitations of the AASHTO Model

- Does not fully account for heavy vehicles (longer stopping times)
- Does not differentiate between various highway types
- Does not recognize differing roadway conditions

Proper roadway design should address these variables by providing more than minimum stopping sight distance at locations with vehicle conflicts or hazardous conditions (sharp curves, cross-section changes, intersections, etc.).

DECISION SIGHT DISTANCE (DSD)

Certain situations requiring complex decisions or maneuvers (unexpected conflicts, navigational needs, roadway changes, etc.) can place extra demands on drivers. These circumstances usually require longer sight distances than those for stopping.

Decision sight distance recognizes these needs and is composed of the following required actions:

Detect unexpected/unusual conflict
Recognize potential risk
Select appropriate speed /path
Initiate and complete safe maneuver

Decision sight distance values are substantially greater than those for Stopping Sight Distance since DSD provides an additional margin of error and sufficient maneuver length at vehicle speeds – *rather than just stopping*.

Decision sight distance is needed for a variety of roadway environments – such as bridges, alignment changes, interchanges, intersections, lane drops, congested intersections, median crossovers, roadway cross-section changes, toll facilities, and unusual geometric configurations.

DSD values depend on whether the roadway's location is rural or urban, and the type of avoidance maneuver required.

Avoidance Maneuver	Condition	Time (sec)
A	Stop on rural road	3.0
B	Stop on urban road	9.1
C	Change on rural road	10.2 to 11.2
D	Change on suburban road	12.1 to 12.9
E	Change on urban road	14.0 to 14.5

The "Green Book" provides tabular decision sight distances to provide appropriate values for critical locations, and to furnish suitable evaluation criteria of available sight distances. Critical decision points need to have sufficient DSD.

Decision Sight Distance

Design Speed (mph)	Decision Sight Distance (ft)				
	Avoidance Maneuver				
	A	B	C	D	E
30	220	490	450	535	620
40	330	690	600	715	825
50	465	910	750	890	1030
60	610	1150	990	1125	1280
70	780	1410	1105	1275	1445
80	970	1685	1260	1455	1650

Source: AASHTO "Green Book" Table 3-3

The pre-maneuver time for avoidance maneuvers is greater than the brake reaction time for Stopping Sight Distance. This gives drivers extra time to recognize the situation, identify alternatives, and initiate a response. DSD pre-maneuver components typically range from **3.0 to 9.1 seconds.**

For Avoidance Maneuvers A and B, the braking distance (for design speed) was added to the pre-maneuver component. Decision sight distances for **Avoidance Maneuvers A and B** can be calculated using the following formula:

$$DSD = 1.47Vt + 1.075\frac{V^2}{a}$$

DSD = decision sight distance (feet)

V = design speed (mph)

a = driver deceleration rate (ft/sec^2)

t = pre-maneuver time (seconds)

For Avoidance Maneuvers C thru E, the braking component is replaced with maneuver distance based on times (3.5 to 4.5 seconds) that decrease with increasing speed. Decision sight distances for **Avoidance Maneuvers C, D, and E** can be calculated from the following equation:

$$DSD = 1.47Vt$$

DSD = decision sight distance (feet)

V = design speed (mph)

t = total pre-maneuver and maneuver time (sec)

PASSING SIGHT DISTANCE (PSD)

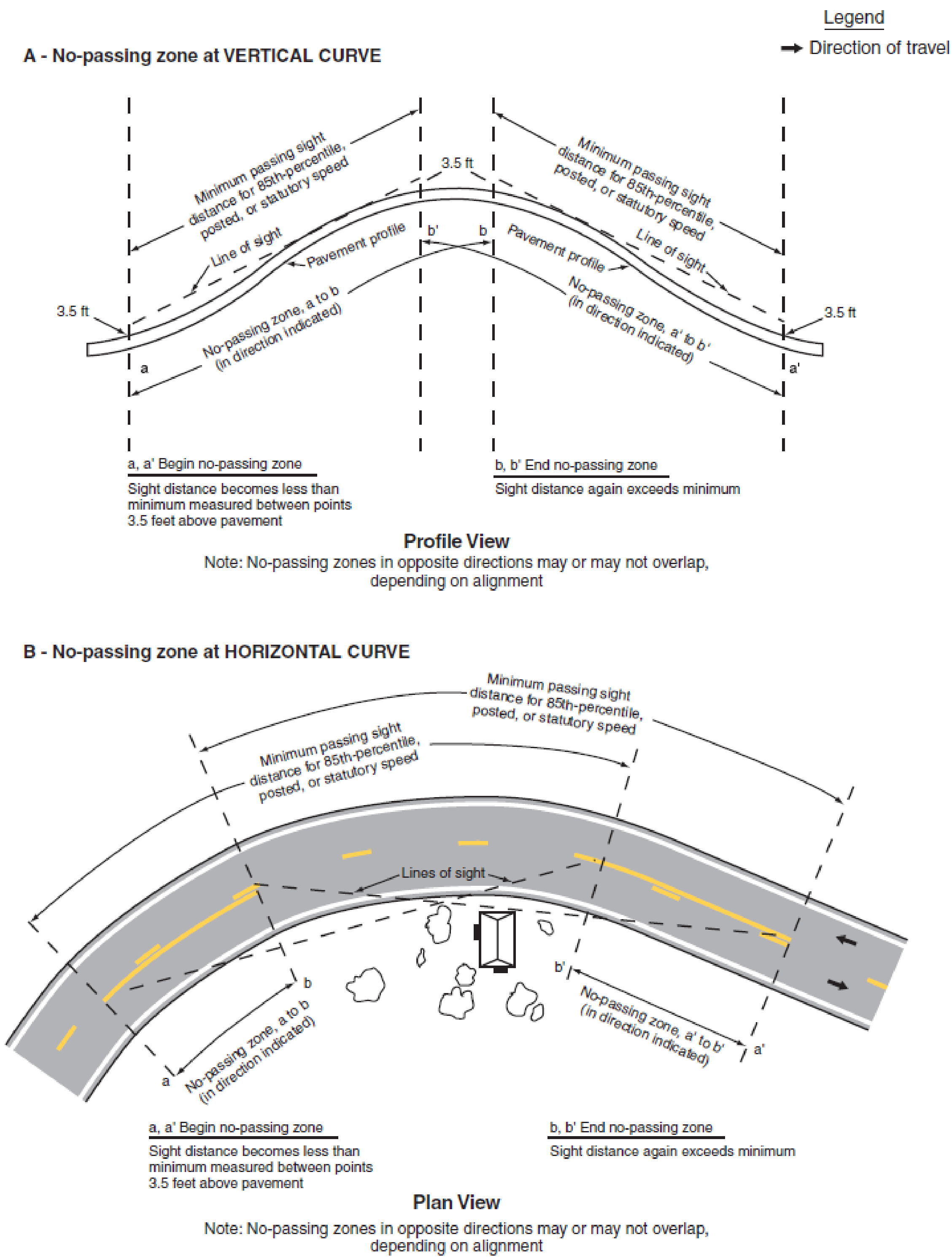
Passing sight distance is the length of roadway needed for drivers on two-lane two-way highways to pass slower vehicles without meeting opposing traffic.

Passing Sight Distance Definitions

Vertical Curve Distance where an object (3.5 ft above roadway surface) can be seen from a point 3.5 ft above the roadway

Horizontal Curve Distance measured (along center line or right-hand lane line for 3-lane roadway) between two points 3.5 ft above the roadway on a tangent line

Figure 3B-4. Method of Locating and Determining the Limits of No-Passing Zones at Curves



Source: MUTCD 2009 Edition

Potential passing conflicts are ultimately determined by driver responses to:

- View of roadway ahead
- Passing and no-passing zone markings

Horizontal alignment is also crucial to determine the location, extent, and percentage of passing distances. More sight distance is required for passing maneuvers than for stopping sight distance which is continuously provided along roadways.

Minimum values for passing sight distances are based on Manual on Uniform Traffic Control Devices (MUTCD) warrants for no-passing zones on two-lane highways. These values are suitable for single or isolated passes only.

Table 3B-1. Minimum Passing Sight Distances for No-Passing Zone Markings

85th-Percentile or Posted or Statutory Speed Limit	Minimum Passing Sight Distance
25 mph	450 feet
30 mph	500 feet
35 mph	550 feet
40 mph	600 feet
45 mph	700 feet
50 mph	800 feet
55 mph	900 feet
60 mph	1,000 feet
65 mph	1,100 feet
70 mph	1,200 feet

Source: MUTCD 2009 Edition

Driver Behavior Assumptions

- Passing and opposing vehicle speeds are equal to the roadway design speed
- Speed differential between passing and passed vehicle is 12 mph
- Passing vehicle has adequate acceleration capability to reach speed differential (40% of way through passing maneuver)
- Vehicle lengths are 19 feet
- Passing driver's perception-reaction time to abort passing maneuver is 1 second
- Deceleration rate of 11.2 ft/s^2 for passing vehicle when passing maneuver is aborted
- Space headway between passing and passed vehicles is 1 second
- Minimum clearance between passing and opposed vehicles upon return to normal lane is 1 second

Design passing sight values should also be based on a single passenger vehicle passing another single passenger vehicle.

Passing sight distances should be should be as long and frequent as possible, and equal or greater than the minimum values, depending on:

- **topography**
- **design speed**
- **cost**
- **intersection spacing**

While passing sections are used on most highways and selected streets, others can usually be provided at little or no additional cost.

INTERSECTION SIGHT DISTANCE (ISD)

The potential for vehicular conflicts at intersections can be greatly reduced with proper sight distances and traffic control. Intersection efficiency depends on driver behavior – judgment, capability, and response. Approaching drivers need an unobstructed view of the intersection and approaching roadways to safely maneuver through the facility.

Intersection sight distance is the length of roadway along the intersecting road that the approaching vehicle should have to perceive and react to potential conflicts. Both roadway horizontal and vertical geometry can have a great effect on ISD.

Sight distance is needed to allow stopped vehicles a sufficient view of the intersecting roadway in order to enter or cross it. Intersection sight distances that exceed stopping sight distances along major roads are considered sufficient to anticipate and avoid conflicts. Intersection sight distance determination is based on many of the same principles as stopping sight distance.

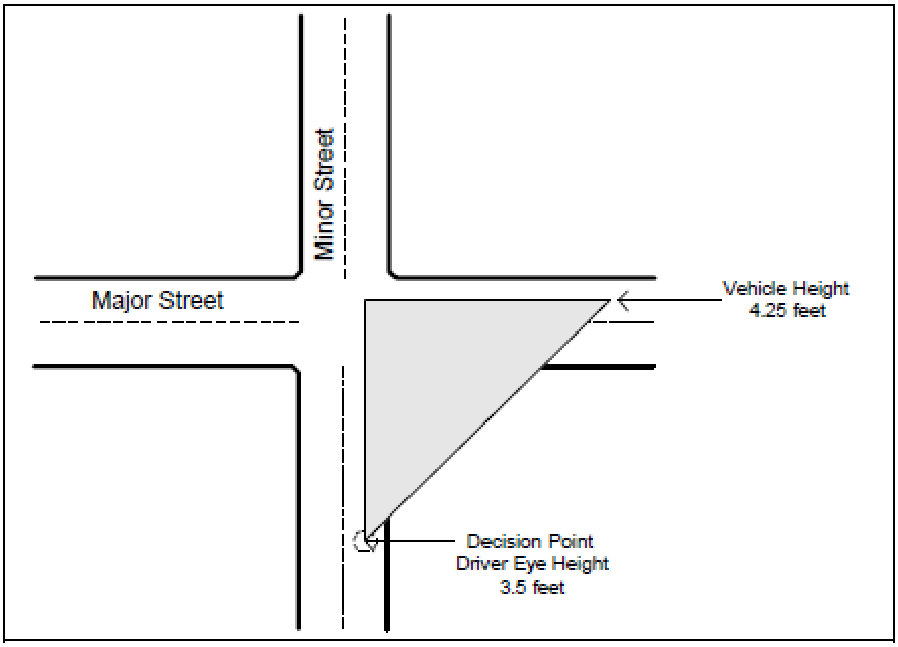


Figure 4.3. Heights Pertaining to Sight Triangles

Source: CTRE – Iowa State University

Clear sight triangles are areas along intersection approach legs that should be without any obstructions that could obscure any potential conflicts from the driver's view. For sight obstruction determination, the driver's eye is assumed to be **3.50 feet** above the road surface, and the visible object is **3.50 feet** above the intersecting road's surface. The dimensions are based on driver behavior, roadway design speeds, and type of traffic control. Object height is based on vehicle height of **4.35 feet** (15th percentile of current passenger vehicle height minus an allowance of 10 inches).

Approach sight triangles are triangular areas free of obstructions that could block approaching a motorist's view of potential conflicts. Lengths of the area legs should permit drivers to observe any potential conflicts and slow, stop, or avoid other vehicles within the intersection. These types of sight triangles are not needed for intersections controlled by stop signs or traffic signals.

Departure sight triangles provide adequate distance for stopped drivers on minor roads to depart the intersection and enter/cross the major road. These sight triangles are needed for quadrants of each intersection approach controlled by stop or yield conditions.

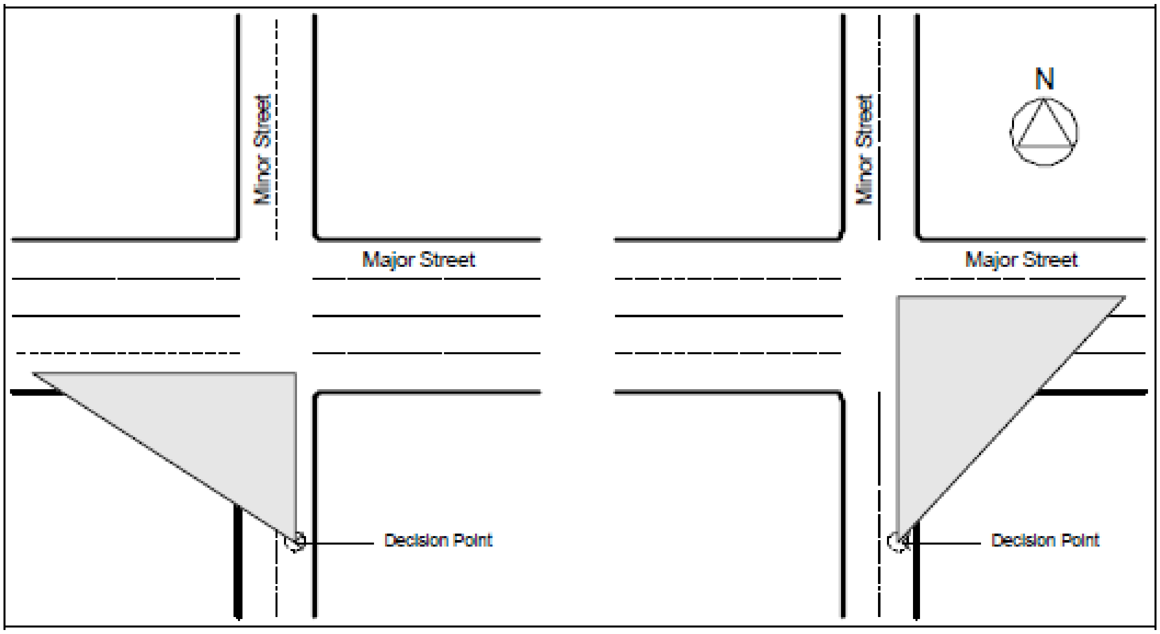


Figure 4.1. Approach Sight Triangles

$$ISD = 1.47V_{major} + t_g$$

ISD = intersection sight distance (along major road) (feet)

V_{major} = design speed of major road (mph)

t_g = time gap for minor road vehicle to enter major road (sec)

AASHTO's method for determining intersection sight distance is fairly complicated (speeds, traffic control, roadway cross-sections, obstruction location, vehicle types, maneuvers). Obstructions include building setbacks, trees, fences, etc. Railroad grade crossing sight distances to adjacent roadway intersections should also be addressed for intersection design and sight distance.

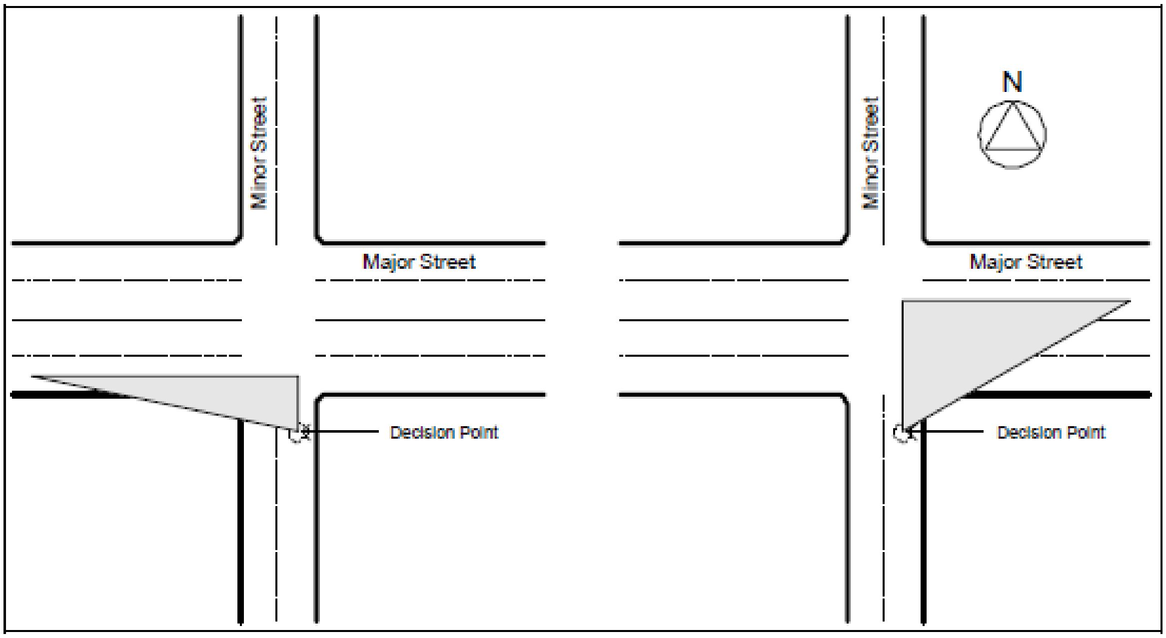


Figure 4.2. Departure Sight Triangles

Source: CTRE – Iowa State University

Methods for determining intersection sight distance vary according to the different types of traffic control:

- **Case A:** Intersections with no control
- **Case B:** Intersections with stop control on the minor road
  - **Case B1:** Left turn from the minor road
  - **Case B2:** Right turn from the minor road
  - **Case B3:** Crossing maneuver from the minor road
- **Case C:** Intersections with yield control on the minor road
  - **Case C1:** Crossing maneuver from the minor road
  - **Case C2:** Left or right turn from the minor road
- **Case D:** Intersections with traffic signal control
- **Case E:** Intersections with all-way stop control
- **Case F:** Left turns from the major road

VERTICAL ALIGNMENT

A proposed roadway must consider the existing constraints and balance safety/economic factors to produce roads that are not either flat or straight with vertical and horizontal curves to accommodate existing conditions (topography, property owners, land usage, natural resources, cost, environment, etc.).

Roadway vertical alignments consist of crest and sag curves with straight grades connecting them. The vertical profile is typically displayed as a graph with elevation on the vertical axis, and horizontal alignment distance on the horizontal axis. Geometric design of the proposed profile is governed by safety, vehicle operations, drainage, and construction issues.

Topography of the land to be traversed plays a major role in the alignment of roadways – particularly the vertical profile. The terrain can be classified by its variations into the following categories:

> ***Level:*** Sight distances are generally lengthy or accomplished without difficulty or expense.
>
> ***Rolling:*** Natural slopes rise or fall below the road grade with occasional steep slopes with some alignment restriction. Typically generates steeper grades than level terrain which causes significant reduction in truck speeds.
>
> ***Mountainous:*** Abrupt changes in ground elevation with respect to the roadway. Benching and excavation are typically used for sight distance. Truck speed reduction will be more drastic.

Rolling terrain typically requires steeper grades than level topography which produce truck speeds below those of passenger cars. Mountainous terrain may cause trucks to operate at much slower (crawl) speeds.

More complex construction methods for increasingly challenging terrain must be used to integrate proposed alignments with the existing ground. The roadway vertical alignment should be coordinated with existing topography, available right-of-way, utilities, developments, and drainage patterns.

TANGENT GRADES

Vertical grades should encourage consistent operation throughout the proposed roadways. AASHTO guidelines for grades are a function of highway type, design speed, and terrain. Most passenger cars can readily negotiate grades as steep as 4 to 5 percent without a significant loss in normal roadway speeds. However, vehicle speeds decrease progressively with grade increases particularly for cars with high weight/power ratios.

Research has shown that passenger car operation on 3 percent upgrades has only a minimal effect on vehicle speeds compared to those on level terrain.

Steep upgrades → speed decreases progressively with grade increases
Downgrades → speed is generally higher than level sections

Truck speeds are much more impacted by vertical grades than passenger cars. Heavy vehicles often control traffic speeds on uphill grades due to restrictive sight distances. Long grades (greater than 3%) influence passenger vehicle speeds while shorter, steeper grades affect truck speeds. This can reduce roadway capacity and create rear-end conflicts. Although both car and truck average speeds are similar for level sections, trucks usually increase downgrade speeds up to 5% and decrease upgrade speeds by 7%. Maximum speeds are dependent on the grade (length and/or steepness) and the truck's weight/power ratio (gross vehicle weight divided by the net engine power).

Truck travel times and speeds are byproducts of their weight/power ratio - present acceptable highway values of approximately 200 lb/hp. Vehicles with similar weight/power ratios produce similar operational results which are useful in anticipating truck performance. Over the years, these values have steadily decreased to produce greater power and better climbing ability on roadway upgrades.

Typically, vertical grades should be less than the maximum design grade (which should be rarely used). Design guidelines for maximum grades have been developed from present grade controls. Although these grades are valuable tools for roadway design, they are not a complete design control. The grade lengths should also be evaluated in related to the desired road's operationality.

Design Speed	Maximum Grade
70 mph	5%
30 mph	7 to 12% (depending on terrain)

Maximum grades of 7 to 8 percent are typical for 30 mph design speed for major routes. For one-way downgrades (less than 500 ft in length), the maximum grade value needs to be approximately 1% steeper than other locations. Maximum grades may be 2% steeper for low-volume rural highways.

Retaining adequate minimum grades can be a critical concern at many roadway locations. These grades are provided for drainage purposes and depend on rainfall, soil type, and site conditions. A typical minimum grade value of 0.5 percent is adequate for roadway surface drainage. For locations with flat grades, stormwater drainage systems (pipes, inlets, swales, channels, etc.) should be considered to keep the spread of water within acceptable limits. Roadway vertical alignments (profile) can affect road drainage by creating steep roads with high velocity flows or flat roads/sag curves with poor drainage.

0.5 percent	Typical minimum grade value
0.3 percent	Minimum control in some states
0 percent (flat)	Should be avoided – relies totally on roadway cross-slope for drainage

Critical Length of Grade

For roadway design, the critical grade length is the maximum length of upgrade on which a loaded truck may operate without an unacceptable speed reduction. These lengths are based on the weight-to-horsepower ratio of loaded trucks. Lengths less than the critical length produce acceptable vehicle operation for the desired speeds. A speed-reduction criterion of 10 mph is used in design for determining the critical length.

Design methods for determining the critical length of grade are intended to be guidelines and not strict regulations. Situations (terrain, physical controls, etc.) may require shortening or flattening grades for the proposed roadway.

Critical lengths of grade may be determined by using the following data:

- *Size , power, and gradeability data for truck*

A typical loaded truck used as a design control has a weight/power ratio of 200 lb/hp

- *Critical length entrance speeds*

The average running speed can be used for vehicle speeds at the beginning of an uphill approach

- *Minimum tolerable speeds of trucks on upgrades*

Roadways designs should strive to prevent intolerable truck speed reductions for following drivers

Typical methods for identifying the critical length of grade have been to use a reduction of 15 mph below the average running speed of all traffic. While it would be ideal for all traffic to operate at average speed, this is not practical. Crash involvement rates increase significantly for truck speed reductions over 10 mph – the rate is 2.4 times greater for 15 mph reduction versus a 10 mph reduction. History has shown that the greater the deviation from the average roadway speed, the greater chance of crashing.

CLIMBING LANES

Climbing lanes are additional lanes used exclusively for slow-moving vehicles (uphill) in order to permit other vehicles on normal roadway lanes to pass. Locations for climbing lanes are suitable for locations where truck speed or level of service is significantly less on upgrades than on the upgrade's approach. Truck climbing lanes are typically recommended on arterials for grades that exceed the critical length of grade.

Two-lane highways with a climbing lane are not considered to be a three-lane roadway – but a highway with an added lane so vehicles using normal lanes are not delayed. Separate climbing lanes for slower vehicles are preferable to adding extra mixed traffic lanes.

Justification Criteria for Climbing Lanes

- Upgrade traffic flow rate exceeds 200 vehicles per hour
- Upgrade truck flow rate exceeds 20 vehicles per hour
- One of the following exists:
  - 10 mph or greater speed reduction expected by heavy trucks
  - Level of service of E or F on grade
  - Reduction of two or more levels of service from approach segment to grade

Climbing lanes may prevent reconstructing existing roads by providing an inexpensive way to reduce crashes, overcome capacity reductions, and improve operation in truck congestion areas. Climbing lanes on new projects can increase operational efficiency without creating a multilane roadway.

Methods for Increasing Passing Opportunities (2-Lane Roads)

Passing lanes
Turnouts
Shoulder driving
Shoulder use sections

A **passing lane** is an added for improving traffic in low capacity sections to the level of their adjacent sections. Passing lanes are frequently provided systematically at regular intervals. Optimal lane lengths are typically 0.5 to 2 miles (longer lane lengths for higher traffic volumes).

Appropriate locations for passing lanes should appear logical to the user and consider the location of intersections, high-volume driveways, physical constraints, and sight distance.

Transition tapers at the ends of added-lane sections may be determined from the following equations:

$$L = WS$$ 45 mph or greater

$$L = \frac{WS^2}{60}$$ Less than 45 mph

L = taper length (feet)

W = width (feet)

S = speed (mph)

Passing lanes need to be long enough to complete at least one passing maneuver – minimum length of 1000 ft (excluding tapers). Passing lane lengths above 1.0 mile provide diminishing operational benefits and may be more appropriate for high volume facilities (over 700 vehicles/hour).

The recommended minimum sight distance for taper approaches is **1000 feet.**

Optimal Passing Lane Lengths

One-Way Flow Rate (veh/h)	Passing Lane Length (mile)
100 to 200	0.5
201 to 400	0.50 to 0.75
401 to 700	0.75 to 1.00
701 to 1200	1.00 to 2.00

Source: AASHTO "Green Book" Table 3-31

Passing Lane Design Procedure

1. Both horizontal and vertical alignments should provide as much passing sight distance as possible

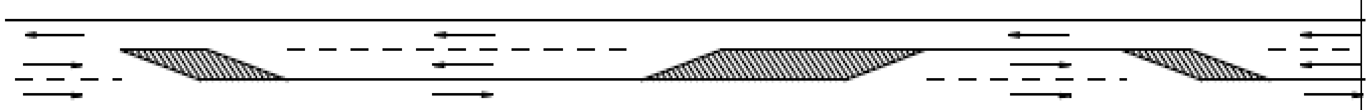
2. The level of service may be reduced as design volume approaches capacity

3. Additional climbing lanes may be needed at locations where the critical length of grade is less than the length of an upgrade

4. If passing opportunities are still restricted after applying the previous measures, passing lanes may still be considered

A **2+1 roadway** has a continuous three-lane cross-section striped for passing lanes that alternate directions throughout. This design can be used to improve operational efficiency and reduce highway crashes. The 2+1 roadway is typically used where four-lane highways are considered not feasible due to environmental/economic constraints, traffic volume requirements, etc. Using this concept generally improves the level of service at least two levels higher than typical two-lane highways.

The 2+1 design should be avoided at locations with flow rates over 1200 vehicles per hour for one direction of travel - four-lane highways are better suited for high flow rates. This type of roadway should also be limited to level and rolling terrain - climbing lanes are better suited for mountainous terrain and steep grades.



Major intersections and driveways are crucial for determining passing lane locations (proper location will minimize turning movements). These high-volume intersections should be placed in the transition between opposing passing sections with left-turn lanes at the intersection. Low-volume intersections and ramps can be installed within the passing lanes.

Sight Distance	**2+1 Roadway Location**
Stopping	Provided continuously
Decision	Intersections & lane drops

A **turnout** is a widened, unobstructed shoulder available for slow-moving vehicles to pull over and allow passing opportunities to other traffic. The typical time for slower vehicles in a turnout depends on the number of following vehicles. For one or two vehicles, the slower vehicle may not have to stop in the turnout for the vehicles to pass. When this number of following vehicles is exceeded, typically the slow-moving vehicle will need to stop. Turnouts are suited for lower volume without heavy traffic or steep grades (mountains, beaches, scenic areas with over 10% heavy vehicle traffic).

Recommended turnout lengths assume that slow-moving vehicles enter the turnout at 5 mph slower than the through traffic's average speed. These lengths include tapers for entries and exits. Turnout lengths shorter than 200 feet are not recommended for use. Lengths over 600 feet are not recommended for high-speed roads in order to prevent its use as a passing lane.

Typical entry & exit taper lengths:	50 to 100 feet
Minimum turnout width:	12 feet (16 feet desirable)
Minimum sight distance:	1000 feet on approach

The minimum turnout lengths range from 200 ft @ 20 mph approach speed to 600 ft @ 60 mph.

Shoulder driving generally occurs when slow-moving vehicles move over to adequate paved shoulders when approached from the rear and then return to the roadway after being passed. In this instance, these shoulders function as continuous turnouts. The practice of shoulder driving is a driver courtesy – a way to provide passing opportunities without a capital investment. However, shoulder driving is currently prohibited by law in many states. Legislation plus public education may be needed to enact any changes permitting this practice.

The amount and structural quality of two-lane roadways should be evaluated before use as a passing opportunity. Shoulder driving may not be limited to selected areas with paved shoulders but anywhere in the roadway system.

Shoulder should have a minimum of 10 feet (12 feet desired). The possible effects that shoulder driving may have on bicycles needs to be considered. No special signing to promote shoulder driving has been created.

Shoulder use sections provide passing opportunities for slow-moving vehicles at designated paved shoulder locations with specific signs. These sections differ from shoulder driving by being a limited application of shoulders that act as extended turnouts.

Slow-moving vehicles move over to the shoulder long enough for faster vehicles to pass and return to through traffic.

Shoulder-Use Section Dimensions

Lengths	0.2 to 3 miles
Width	10 feet (12 feet desired)

Special signs should be installed at the beginning and end of shoulder-use sections. Existing shoulder condition needs to be evaluated for structural strength to support anticipated traffic loads. Good surface conditions (free of debris without rough or broken sections) are needed to encourage driver use.

EMERGENCY ESCAPE RAMPS

An emergency escape ramp should be used where roadway grades (due to their steepness and length) create an opportunity for potential out-of-control vehicles. Emergency escape ramps need to be provided as soon as a need is established. Contributing factors for runaway vehicles include roadway grades, alignment, length, and descending speed.

Typical Causes of Out-of-Control Vehicles

Brakes:	overheating or mechanical failure
Transmission:	failure to downshift properly, etc.

Effective escape ramps help save lives and reduce property damage by providing proper deceleration rates and good driver control. These ramps should be designed for the worst case scenario, where the speeding vehicle is out of gear with brake system failure. Crash histories and potential community impacts combined with engineering judgment are typically used to see if an escape ramp is warranted.

Each emergency escape ramp presents a variety of factors unique to its specific location, such as:

Topography
Percentage and length of grade
Potential speed
Economics
Environmental impact
Crash history

Emergency escape ramps are usually built tangent to main roads and in advance of any horizontal curves that cannot be safely negotiated. Theses ramps should also exit to the right of the highway.

The maximum speed for an out-of-control vehicle should be used as the design speed for the escape ramp. A recommended entering design speed of **80 to 90 mph** represents an extreme situation that should not be the determinant for choosing potential ramp locations.

The need for an emergency escape ramp should be based on **safety** – the safety of other roadway traffic; the safety of the runaway vehicle driver; and the safety of residents along the roadway.

The minimum entering speed for emergency escape ramps is **80 mph** (90 mph preferred).

Emergency Escape Ramps Categories

- **Gravity** (least desirable)
  - Stops forward motion but does not prevent rollback
  - Paved or densely compacted aggregate surface
  - Usually long, steep and constrained by topography and costs

- **Sandpile** (less desirable)
  - Loose, dry sand
  - Maximum length of 400 feet
  - Suitable for areas with compact dimensions
  - Severe deceleration characteristics and weather affects

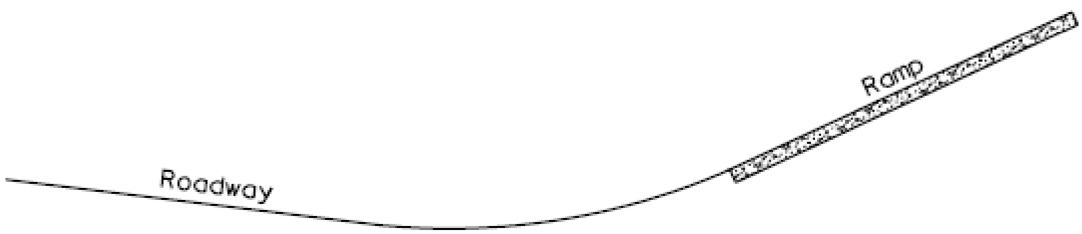
- **Arrester bed**
  - Descending grade
    - Parallel and adjacent to through lanes
    - Loose aggregate to slow vehicle
    - Lengthy ramps may require return paths
  - Horizontal grade
    - Flat grade to slow or stop vehicles
    - Minimal effect
    - Lengthier ramps required
  - Ascending grade
    - Most common
    - Aggregate increases rolling resistance and holds vehicles in place
    - Reduces ramp length

Within these categories, there are four basic ramp designs - *sandpile, descending grade, horizontal grade,* and *ascending grade* (most common).

Sandpile

Descending Grade

Horizontal Grade



Ascending Grade

Guidelines for Effective Escape Ramps

- Length should be sufficient to dissipate vehicle kinetic energy
- Alignment should be tangent or flat curvature
- Width should be able to hold more than one vehicle
  (minimum width of 26 feet, 30 to 40 feet desirable)
- Arrester bed aggregate should be clean, rounded, uncrushed, similar size, and free of fine-sized material *(AASHTO No. 57 is typically used)*
- Arrester beds should have a minimum aggregate depth of 3 feet with a recommended depth of 42 inches *(3.5 feet)*
- Arrester bed grading should have sufficient drainage to prevent freezing or contamination
- Ramp entrances should be designed for vehicles operating at high speeds
  (provide as much sight distance as possible)
- Exit signage should clearly indicate ramp access and allow adequate driver reaction time
- A service road *(10 ft minimum width)* should be located adjacent to the arrester bed for tow truck/maintenance vehicle access
- Anchors should be located at 150 to 300 foot interval adjacent to the arrester bed for tow truck operations *(one anchor installed 100 feet in advance of the bed)*

VERTICAL CURVES

Roadway vertical alignments consist of tangent grades connected with either crest (convex) or sag (concave) parabolic curves. These curves provide a gradual grade change for vehicles to smoothly navigate from one grade to another.

<u>Parabolic Curve Advantages</u>

Straightforward computations
Good riding comfort
Easy field implementation

Design guidelines for vertical curve lengths are based on sufficient sight distance and driver comfort. The resulting vertical curves should be a simple design with proper sight distance, enhanced vehicle control, pleasing appearance, and adequate roadway drainage.

Sight Distance

Sufficient sight distance is a major design control for crest vertical curves. All curves should be designed to provide adequate stopping sight distance at a minimum – with longer distances where possible to ease any shock from grade changes.

Driver Control

Changing roadway vertical grades need to tolerable for driver comfort and control. This grade rate of change is critical for sag curves where gravitational and vertical forces act in opposite directions.

Appearance

Vertical curve designs should also be pleasing in appearance. Shorter curves may be perceived as abrupt breaks in the vertical alignment and may not project as pleasing an appearance as long vertical curves.

Roadway Drainage

Special attention should focus on designing sag vertical curves for proper drainage. It is important to maintain *a minimum grade of 0.5 percent* (0.3% for outer roadway edges). However, it may be necessary to use flatter grades in some instances.

Terms

A = algebraic difference in grades (percent)
VPC = begin of vertical curve
VPT = end of vertical curve
G1 = initial roadway (tangent) grade
G2 = final roadway (tangent) grade
h_1= Height of eye above roadway surface
h_2= Height of object above roadway surface
L = vertical curve length
VPI = vertical point of interception
(intersection of initial and final grades)

Parabolic curves for vertical roadway profiles are stationed in the horizontal plane and consist of an equivalent vertical axis centered at the intersection of the tangent grades (VPI). This means that one-half of the length is before the VPI with the other half after it. The parabolic curve functions produce a constant rate of change of slope.

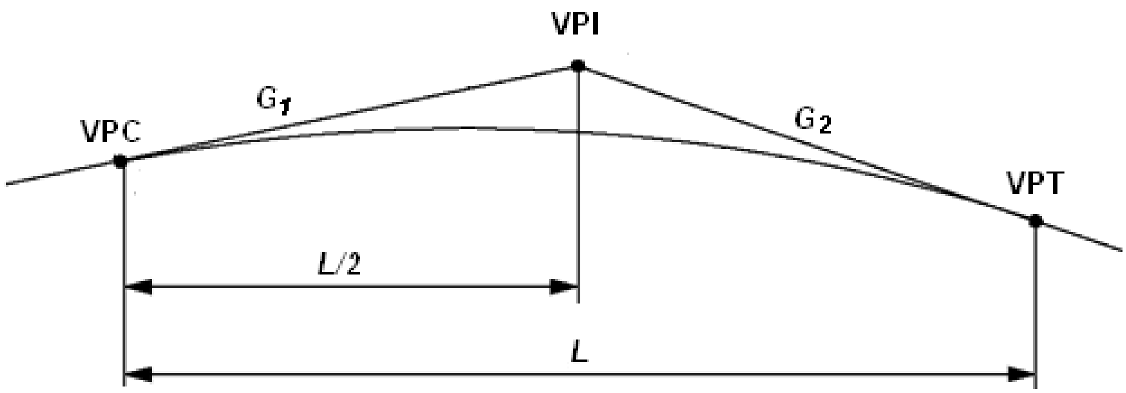
The **K value** is the horizontal distance needed to create a one-percent change in grade. It is a measure of curvature that is expressed as the ratio of the vertical curve length to the algebraic difference in the grades (L/A). For vertical curve design, K is based on design speed and the type of curve. K values are useful for computing distances from VPC's to sag and crest points or for calculating minimum vertical curve lengths (L=KA).

CREST VERTICAL CURVES

Crest (convex) vertical curves typically appear as a hill and have a lower tangent slope at the end of the curve than at its beginning - with vehicles first going uphill, reaching the top of the curve and then continuing downhill.

Crest curves are formed where two grades meet in any of the following conditions:

- one positive grade meets another positive grade
- a positive grade meets a flat grade
- an ascending grade meets a descending grade
- a descending grade meets another descending grade



Stopping Sight Distance Parameters

Stopping sight distance is the distance visible over the vertical curve's crest. It is a crucial design criterion for these curves and its distance is determined by the speed of roadway traffic. Horizontal curves should not be located beyond the vertical crest in a way that prevents the user from seeing upcoming horizontal changes. All vertical curves (both sag and crest) need to be coordinated with the roadway's horizontal alignment. The appropriate equation depends on the length of vertical curve versus available sight distance.

Figure 4.12. Heights Pertaining to Stopping Sight Distance

Source: CTRE – Iowa State University

The following basic AASHTO formulas are used for determining crest vertical curve lengths in terms of algebraic grade difference (A) and sight distance (S).

When S is less than L

$$L = \frac{AS^2}{100\left(\sqrt{2h_1} + \sqrt{2h_2}\right)^2}$$

When S is greater than L

$$L = 2S - \frac{200\left(\sqrt{h_1} + \sqrt{h_2}\right)^2}{A}$$

L = length of vertical curve (feet)

A = algebraic difference in grades (percent)

S = sight distance (feet)

h_1 = eye height above roadway surface (feet)

h_2 = object height above roadway surface (feet)

Stopping Sight Distance Criteria

Height of Eye:	3.50 feet
Height of Object:	2.00 feet

The crest vertical curve length formulas can be further simplified by using the typical values for eye height and object height to create the following equations.

When S is less than L

$$L = \frac{AS^2}{2158}$$

When S is greater than L

$$L = 2S - \frac{2158}{A}$$

L = length of vertical curve (feet)

A = algebraic difference in grades (percent)

S = sight distance(feet)

Typical minimum vertical curve lengths range from 100 to 325 feet. Minimum lengths may be approximated by using three times the design speed.

$$L_{min} = 3V$$

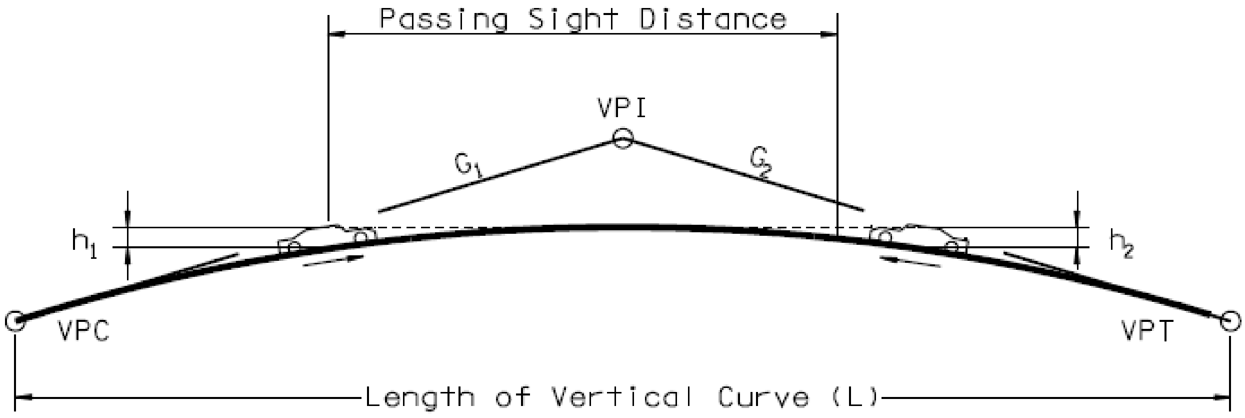
L_{min} = minimum length of vertical curve (feet)

V = design speed (miles per hour)

Roadway visibility at night is defined as the length of road directly illuminated by vehicle headlights. In some cases, minimum stopping sight distances may exceed the stretch of visible roadway

Low-beam headlights regardless of roadway profile
Area forward of light on roadway with shadows and indirect illumination

Vehicle headlight mounting height **(normally 2 feet)** rather than driver eye height **(3.50 feet)** controls the sight distance to an illuminated object. The bottom of the headlight beam is typically **1.30 feet** above the roadway surface at a distance (equal to the stopping sight distance) ahead of the vehicle. Assumed taillight height varies from **1.50 to 2.00 feet**.



Passing Sight Distance Parameters

Passing sight distance design values for vertical curves vary from stopping sight values due to their different sight distance and object height specifications. Minimum lengths of crest vertical curves are substantially longer for those based on passing sight distances compared with stopping values. Passing sight distance controls are typically not used due to the high costs of crest cuts and difficulty of integrating long vertical curves with existing topography.

Crest vertical curve design values for passing sight distance may be determined from the following AASHTO formulas.

When S is less than L

$$L = \frac{AS^2}{2800}$$

When S is greater than L

$$L = 2S - \frac{2800}{A}$$

L = length of vertical curve (feet)

A = algebraic difference in grades (percent)

S = sight distance (feet)

Passing sight criteria for crest curves may be appropriate for:

- Low speed roadways with gentle grades
- High speeds with small grade differences
- Locations not needing significant grading

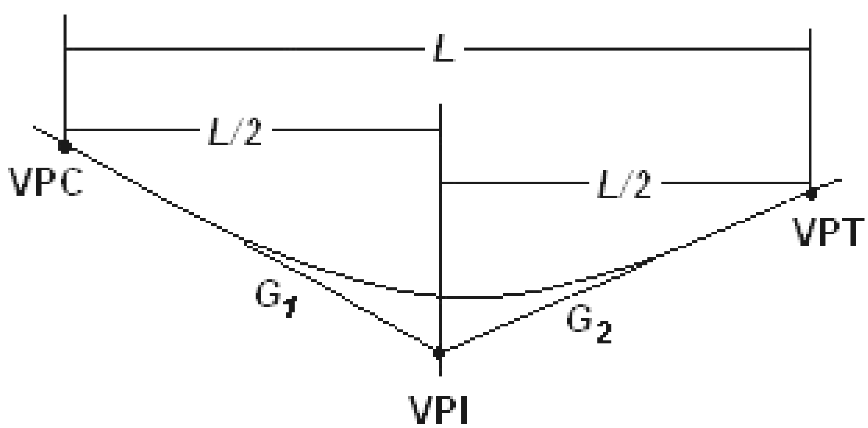
Crest Vertical Curve Design Controls

Design Speed (mph)	Passing Sight Distance (ft)	Rate of Vertical Curvature *K* Design
20	400	57
30	500	89
40	600	129
50	800	229
60	1000	357
70	1200	514
80	1400	700

Source: AASHTO "Green Book" Table 3-35

SAG VERTICAL CURVES

Sag (concave) vertical curves appear as valleys by having a tangent slope at the curve end which is higher than at the beginning – with vehicles first going downhill, reaching the bottom of the curve, and continuing uphill.



Sag Vertical Curve Length Criteria

Headlight sight distance
Passenger comfort
Drainage control
General appearance

Headlight sight distance is the main determinant for sag curve length. This is limited by the headlight position and direction when traveling at night. Visibility must be adequate for a driver to see an obstruction and stop within the headlight sight distance. Sag curve length should be sufficient for the light beam to illuminate the roadway and provide adequate stopping sight distance. This permits drivers to see the roadway ahead. Short sag curve lengths can be used for roadway locations that are illuminated or limited by severe geometric constraints. Limiting values are related to studies of driver comfort.

Headlight Sight Distance Assumptions

Headlight height: 2 feet
Upward divergence of light beam from longitudinal axis of vehicle: 1 degree

$$L = \frac{AV^2}{46.5}$$

L = length of sag vertical curve (feet)

A = algebraic difference in grades (percent)

V = design speed (mph)

The effect on user comfort due to change in vertical direction is greater for sag curves due to gravitational and centripetal forces. These changes cannot be easily measured because of various factors including:

- Vehicle body suspension
- Body weight
- Tire flexibility

Historical data concludes that riding on sag curves is comfortable when the maximum centripetal acceleration value is **under 1 ft/s^2.**

Vertical curve lengths needed to satisfy passenger comfort are typically 50% of the headlight sight distance (under normal conditions). A good rule-of-thumb approximation for minimum sag vertical curve length is 100A or K = 100 feet per percent change in grade.

General Controls for Vertical Alignments

- *Smooth, gradual gradeline consistent with roadway type and terrain desired.* Specific design criteria are the maximum grade and critical length of grade. The application and fit in relation to the terrain determines suitability and appearance.

- *Avoid hidden dips/changes in the roadway profile.* These typically occur on straight horizontal alignments with rolling natural ground lines. Dips can create difficulties for passing drivers due to obstructed sight distances.

- *Evaluate any proposed profile containing substantial momentum grades with traffic operations.* This can prevent excessive truck speeds and conflicts with other traffic.

- *Avoid "broken back" (consecutive vertical curves in the same direction) gradelines.* This practice produces a discordant appearance (especially for sag curves) that is especially noticeable on divided highways with medians.

- *Place steep grades at the bottom and flatter grades near the top of ascents.* This is generally used on roadways with low design speeds to break up a uniform sustained grade.

- *Reduce grades through at-grade intersections with moderate to steep grades.* These profile changes help turning vehicles and reduce potential crashes.

- *Avoid sag curves in cut sections, where possible, unless sufficiently drained.*

Minimum lengths for sag curves are based on design speed. Longer curves should be used wherever possible. Special attention should be paid to drainage needs where K values are in excess of **167 feet per percent change in grade.**

Sag vertical curves with shorter than normal lengths may be used for locations where existing features control the vertical alignment.

COORDINATION OF HORIZONTAL AND VERTICAL ALIGNMENTS

Geometric roadway design influences safety performance. Historical crash data has shown that roadway factors are the **second** most contributing factor to roadway accidents. Crashes are more likely to occur at locations with sudden changes in road character (i.e. sharp curves at the end of long tangent sections).

Design consistency compares adjacent road segments and identifies locations with changes that might violate driver expectations. This type of analysis can be used to show operating speed decreases at curves.

Horizontal and vertical geometrics are the most critical roadway design elements. These alignments should be designed concurrently to enhance

vehicle operation,

uniform speed,

and aesthetics without additional costs.

Examples include: checking for additional sight distance prior to major vertical alignment changes; or revising design elements to eliminate potential drainage problems.

Horizontal and vertical alignment geometric designs complement each other while poor designs can reduce the quality of both. It can be extremely difficult and costly to fix any vertical and/or horizontal deficiencies once a roadway is built. Any initial savings can be offset by economic losses due to crashes and delays.

Physical factors that help define roadway alignments include:

- Roadway traffic
- Topography
- Subsurface conditions
- Cultural development
- Roadway termini

Although design speed helps to determine the roadway's location, it assumes a greater role as the design of the horizontal and vertical alignments progress. Design speed aids in balancing all of the design elements by limiting many design values (curves, sight distance) and influencing others (width, clearance, maximum gradient).

General Procedure

Coordinating horizontal and vertical alignments should begin with any roadway preliminary design. Any adjustments or corrections can be readily made at this phase.

Working drawings can be used for studying long, continuous plan and profile views to visualize the proposed three-dimensional roadway. Computer-aided drafting and design (CADD) systems are typically used to create optimal 3-D designs.

After development of a preliminary design, adjustments can be made for better coordination between the alignments. Using the design speed, the following factors should be checked:

Controlling curvature
Gradients
Sight distance
Superelevation runoff lengths

Also, the design controls for vertical and horizontal alignments should be considered, as well as all aspects of terrain, traffic, and appearance. All adjustments should be made before the costly and time-consuming preparation of construction plans.

For local roads, the alignment is impacted by existing or future development – with intersections and driveways being dominant controls. Designs should contain long, flowing alignments instead of a connected series of block-by-block sections.

AASHTO Design Guidelines for Horizontal and Vertical Alignments

- Vertical and horizontal elements should be balanced to optimize safety, capacity, operation, and aesthetics within the location's topography.

- Both horizontal and vertical alignment elements should be integrated to provide a pleasing facility for roadway traffic.

- Sharp horizontal curves near the top of a crest vertical curve or near the low point of a sag vertical curve should be avoided. Using higher design values (well above the minimum) for design speed can produce suitable designs and meet driver's expectations.

- Horizontal and vertical curves need to be as flat as possible for intersections with sight distance concerns.

- For divided roadways, It may be suitable to vary median widths for divided roadways. Independent horizontal/vertical alignments should be used for individual one-way roads.

- Horizontal and vertical alignments should be designed to minimize impact in residential areas. Typical applications include:

    depressed facilities (decreases facility visibility and noise)

    horizontal adjustments (increases buffer zones between traffic and neighborhoods).

- Geometric design elements should be used to enhance environmental features (parks, rivers, terrain, etc.). Roadways should enhance outstanding views or features instead of avoiding them where possible.

Exception: Long tangent sections for sufficient passing sight distance may be appropriate for two-lane roads needing passing sections at frequent intervals.

SUMMARY

Along with the roadway cross section (lanes and shoulders, curbs, medians, roadside slopes and ditches, sidewalks) and horizontal alignment (tangents and curves), the **vertical alignment** (grades and vertical curves) helps provide a three-dimensional roadway model. Its ultimate goal is to provide a safe, smooth-flowing facility that is crash-free. Roadway vertical alignments are directly related to their operational quality and safety.

In today's environment, designers must do more than apply design standards and criteria to 'solve' a problem. They must understand how various roadway elements contribute to safety and facility operation, including the vertical profile.

This course summarizes the geometric design of vertical alignments for modern roads and highways. This document is intended to serve as guidance and not as an absolute standard or rule. For further information, please refer to **AASHTO's A Policy on Geometric Design of Highways and Streets (Green Book)**. It is considered to be the primary guidance for U.S. roadway design. **Section 3.4 – Vertical Alignment** was used exclusively to present fundamental roadway profile geometric design principles.

By completing this course, you should be familiar with the general design of vertical roadway alignments. The objective of this course was to give engineers and designers an in-depth look at the principles to be considered when selecting and designing roads.

This course focused on the following:

- Sight Distance
    - *Stopping*
    - *Decision*
    - *Passing*
    - *Intersection*

- Vertical Alignment
    - *Grades*
    - *Climbing lanes*
    - *Passing opportunities*
    - *Emergency escape ramps*

- Vertical Curves
  - *Sag*
  - *Crest*

- Coordination of Horizontal & Vertical Curves

The fundamental objective of good geometric design will remain as it has always been – **to produce a roadway that is safe, efficient, reasonably economic and sensitive to conflicting concerns.**

REFERENCES

A Policy on Geometric Design of Highways and Streets, 6th Edition
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This text is the source for all equations and tables contained within this course, unless noted otherwise.

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